

BLADE DESIGN AND OPERATING EXPERIENCE
ON THE MOD-OA 200 KW WIND TURBINE
AT CLAYTON, NEW MEXICO

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SUMMARY

A 200 KW wind turbine called MOD-OA is located in Clayton, New Mexico. The MOD-OA wind turbine blade is a 60 foot long aluminum structure, similar in appearance to an airplane wing, that weighs 2,360 lbs. The blades, SN-1004 and SN-1005, accumulated over 3000 hours of operating time between November 1977 and April 1979. Signs of blade structural damage were first observed after 400 hours of wind turbine operation. The blades were removed from the wind turbine for repairs in June 1978. Repairs were completed and the blades were installed on the wind turbine for renewed operation in September 1978. Details of the blade design, loads, cost, structural damage and the blade repair are discussed.

INTRODUCTION

The U. S. Department of Energy (DOE) is responsible for wind turbine development. The management of one phase of the program--large horizontal axis wind turbine development has been assigned to the Lewis Research Center of the National Aeronautics and Space Administration (NASA).

The overall objective of the MOD-OA wind turbine project is to obtain early operation and performance data while gaining experience by operating in a typical utility environment. The first MOD-OA wind turbine became operational at a utility site in Clayton, New Mexico in early 1978.

Because of limited funding and time allowed, a laboratory type of technology development phase of the MOD-OA project was not feasible. Instead, it was decided that wind turbine technology development would be conducted while utility operating experience was being gained.

The objectives for the development of the MOD-OA blades were (a) to test the blades on the wind turbine and not in the laboratory and (b) as technology problems were found, devise

solutions and make the necessary modification to maintain the operational status of the blades. The experience gained as a result of operating the wind turbines on a public utility is part of a planned learning process to develop better performing and lower cost blades.

The MOD-OA blades are designed and constructed in much the same way as an airplane wing. During laboratory structural acceptance tests on airplane wings, detail structural design deficiencies are often found. The deficiencies are repairable by structural modification. Usually the modifications are isolated to a particular region. These problem areas are often called "hot spots." Like airplane wings, the wind turbine blades have developed some "hot spots." As a result the blades have required some structural modifications.

Details of the MOD-OA blade design, loads and cost are discussed in this paper. During early operation of the blades, on the MOD-OA wind turbine, blade structural damage was observed. As a result, structural repair to each blade was needed. The structural blade damage and the necessary repairs are discussed in this paper.

BLADE SPECIFICATIONS

The blade specifications are summarized in Table I. The specifications include the blade dimensions, materials, the airfoil type and the flapwise and chordwise cantilever natural frequencies. The planform of the blade is shown in figure 1. Strain gages are located at the root end and at blade midspan. The strain gages are used to measure the flapwise and chordwise bending moments and torsion. An ice detector is located at mid span. The ice detector provides a signal, during ice build up, that initiates the shutdown of the wind turbine. A twenty-four hole bolting flange at the root end of the blade provides the mechanical interface between the blade and hub of the wind turbine. A fifty-five pin standard electrical connector provides the electrical interface. The connector provides the electrical needs for the strain gages and the ice detector.

DESIGN DETAILS

Figure 2 shows a cross section of the blade, taken at sta 300, also called out in figure 1. The forward portion of the cross section is called the D-spar. The aft portion of the cross section is called the trailing edge. The D-spar is a heavier and stronger portion of the blade and as a result it carries the majority of the applied loads. Angle stringers and ribs, shown in figure 2, are needed to prevent panel buckling, of the .08 inch and the .31 inch thick outer skins, due to compressive loads.

Detail A, called out in figure 2, is shown in figure 3. A typical method of attaching the angle stringers to the D-spar skin and rib is shown in figure 3. The steel Hilok fastener is an aircraft type of high strength bolt. Close tolerance holes must be prepared so that there is an interference fit between each fastener and the hole. The interference fit allows the Hilok fastener to carry high shear loads. Aluminum rivets are typically used in the trailing edge portion of the blade.

Figure 4 shows the design details of the root end of the blade. A steel cylindrical tube slides through the rib at station 48 and is bolted to the rib at station 81.5 and is bolted to the web near station 81.5. The flange at station 31.75 provides the mechanical interface to the hub of the wind turbine.

LOADS AND ANALYSIS

Table II summarizes the maximum safe, or "red line," operating blade bending moments allowed during operation. Blade loads data, taken during operation, show that the loads are generally at or below the "red line" values. However, overloads have infrequently been observed during a yaw maneuver and during an emergency shutdown of the machine. During an emergency shutdown, the blades are pitched at $4^\circ/\text{sec}$. causing a rapid decrease of the rotor speed.

The structural analysis for the MOD-OA wind turbine blade is identical to the standard methods used for aircraft wings (refs. 1 and 2). Further discussion of operational blade loads and analysis is found in ref. 3. Several computer codes are being used to calculate blade loads during simulated operating conditions (ref. 4).

MOD-OA BLADE DESIGN DRIVERS

The DOE/NASA research wind turbine is called MOD-O, and it is located in Sandusky, Ohio (ref. 3). Soon after the MOD-O wind turbine was operating the DOE requested NASA to begin fabricating the first MOD-OA wind turbine. It was necessary that the first MOD-OA machine be completed within certain cost and time requirements. In order to meet the cost and schedule requirements, it was necessary to use the basic MOD-O aluminum blade design for the MOD-OA blades.

During early operational experience with the MOD-O wind turbine, the measured MOD-O blade loads were higher than the loads used to design the blades (refs. 1 and 3). As a result, it was decided to redesign the MOD-O blades, to carry higher loads while maintaining the 50,000 hour life requirement.

During early operational experience with the MOD-OA wind turbine at Clayton, New Mexico some blade design deficiencies were found. Also, certain wind turbine operating conditions were found that imposed blades loads in excess of the design allowables. Structural design changes were devised, and structural modifications were performed on the blades, to correct the design deficiencies. The design changes and structural modifications will be discussed in the section entitled "The Clayton Experience."

COST & COST DRIVERS

Table III summarizes the costs for MOD-OA blades. It is noted that the reduction in cost for the blades (S/N 008, S/N 009) is due to more efficient assembly procedures. Also, the costs shown in Table III are actual costs with no adjustment for inflation.

The process used to fabricate each blade is labor intensive. Each blade is made up of many individual parts, each requiring a number of hand operations during most phases of fabrication. Examples of this highly labor intensive fabrication and assembly process are as follows:

1. Brake forming of the individual D-spar .25 and .31 thick skin panels
2. Hand trimming and fitup of each individual D-spar panel and trailing edge panel
3. Individually drilling, reaming and deburring the majority of the 14,000 holes for fasteners

Additional details on fabrication of the blades are contained in reference 5.

Because a limited number of the MOD-OA blades were to be built, inexpensive wood assembly fixtures were used for the assembly. The tooling required to reduce the labor time was not economically practical for the few blades that were fabricated.

THE CLAYTON EXPERIENCE

On November 30, 1977 the MOD-OA wind turbine was operated in Clayton, N.M. for the first time. Operational checkout of the wind turbine, at Clayton, was conducted by NASA from December 1977 through February 1978. Information on the equipment used to perform operational checkout of the wind turbine is found in reference 5. The wind turbine was turned over to the Town of Clayton Light and Water Plant on March 6, 1978, for routine operation during a two year experimental period. The operational experience gained during the first ten months of utility operation in 1978 is described in reference 6.

In late March 1978, Utility Company personnel reported to NASA that a creaking noise was emanating from the blades. They also reported the appearance of a gray discoloration around several protruding head fasteners. The fasteners were located between station 48 and 80 along the joint connecting the trailing edge to the D-spar. By late March 1978 each blade had accumulated about 400 hours of operation, which is equivalent to about one million load cycles.

In April 1978, NASA inspected the blades at Clayton. As a result of the inspection, two broken fasteners and several loose fasteners were found on one of the blades. These fasteners were located between station 48 and 80 along the joint connecting the trailing edge to the D-spar. Because structural damage to the blade was found, the blades were removed from the wind turbine in June 1978. The blades were then sent to the Lewis Research Center in Cleveland, Ohio for a more thorough inspection of the structure. At the time the blades were removed from the wind turbine in June 1978, the blades had accumulated 1,124 hours of operation at 40 rpm or 2.7×10^6 load cycles. It is important to note the accumulation of a significant number of load cycles (2.7×10^6) over just a few months of wind turbine operation.

As a result of the blade inspection at the Lewis Research Center, two blade design deficiencies were found.

One design deficiency was located along the line of fasteners joining the trailing edge skin to the D-spar, shown in figure 5a. It was determined that the joint, shown in figure 5a, could not carry the applied shear loads. The shear loads occur primarily due to the weight of the blade. As a result broken and loose fasteners were found, and cracks were found in several angle stringers located in the root end end of the D-spar. This design deficiency was corrected by adding doublers, on the exterior of the blade, between station 48 and 100, as shown in figure 6.

The second design deficiency was the bearing interface, located between the aluminum rib, at station 48, and the steel root end fitting, shown in figure 5b. It was observed, during the blade inspection at the Lewis Research Center, that the steel root end fitting had rubbed on the aluminum rib during operation. This rubbing action caused excessive wear of the aluminum rib. The wear resulted in a radial clearance of 0.14 inches between the root end fitting and the rib as shown in figure 5b. Because of the large radial clearance at sta 48, a bending moment, larger than the design allowable, was applied to the rib at station 81.5. The high bending moments applied to the station 81.5 rib caused the rib to crack and also caused the 0.25 thick D-spar skin to crack.

As a result, doublers were added to the blade exterior at station 81.5, as shown in figure 6. A special bearing was designed, as shown in figure 7, to reduce the wear of the aluminum rib at station 48.

The two structural design deficiencies described above are often referred to as structural "hot spots" in the aircraft industry. As in the case of newly developed aircraft, it is not unusual to find hot spots during the early operation of a new wind turbine blade structure. The structural damage can be classified as a hot spot because the damage occurred over a short spanwise portion of the blade, between station 48 and station 100.

The structural modifications to the blades were completed at the Lewis Research Center, and the blades were returned and installed on the Clayton wind turbine in September 1978.

In April 1979, the blades had accumulated about 3000 hours of operating time or 7.3×10^6 load cycles. The blade structure, outboard of station 100, appears to be in good condition and shows no evidence of structural degradation.

ALTERNATE MODIFICATIONS

Figure 8 shows an alternate method for securing the steel root end fitting to the blade. This modification is currently being made to the MOD-O aluminum wind turbine blades. This design eliminates the need for a bearing at station 48. A new steel rib, installed at station 69, carries load from the new root end fitting directly into the D-spar. The new rib at station 69 eliminates the need for the rib at station 81.5. As a result, no structural modification to the heavily damaged rib at station 81.5 was needed. When the blades are complete, they will be installed and operated on a MOD-OA wind turbine. Operational experience with the newly modified blades will allow NASA to assess the structural integrity of the new design.

CONCLUSIONS

Periodic inspection of the MOD-OA blades has resulted in the detection of structural damage in the early stages.

The blade structural damage found in June 1978, was repaired and the blades were put back into operation on the MOD-OA wind turbine during September 1978. These repairs have substantially improved the service life of the blades to over 3,000 hours, as of April 1979.

The nominal cost for the six MOD-OA wind turbine blades, purchased by NASA, is \$100/lb. This cost is primarily due to labor intensive fabrication procedures and numerous parts.

REFERENCES

1. Cherritt, A. W. and Gaidelis, J. A.; "100 kW Metal Wind Turbine Blade Basic Data, Loads, and Stress Analysis, DOE/NASA/9235-75/1
2. Peery, David J., "Aircraft Structures" McGraw-Hill Book Co., 1950
3. Linscott, B. S.; Glasgow, J.; Anderson, W. D. and Donham, R. E.; "Experimental Data and Theoretical Analysis of an Operating 100 kW Wind Turbine, DOE/NASA/1028-78/15; NASA TM-72883, January 1978.
4. Spera, D. A.; "Comparison of Computer Codes for Calculating Dynamic Loads in Wind Turbines", DOE/NASA/1028-78/16 NASA TM-73773, Sept. 1977
5. Hunnicutt, C. L.; Linscott, B.; and Wolf, R. A.; "An Operating 200 kW Horizontal Axis Wind Turbine", DOE/NASA/1004-78/14; NASA TM-79034, May 1978
6. Glasgow, J. C.; and Robbins, W. H.; "Utility Operational Experience on the NASA/DOE Mod-OA 200 kW Wind Turbine", DOE/NASA/1004-79/1; NASA TM-79084, February 1979

DISCUSSION

- Q. How much did the blade weight increase due to structural modifications?
- A. About 100 lbs. of structure was added to each blade.
- Q. Did each blade experience similar damage and were the structural modifications to each blade similar?
- A. Both blades experienced similar damage. However, the damage to blade 100 was more severe. As a result the structural modifications to blade 100 were more extensive in detail. However, from outward appearance, the modifications to each blade are nearly identical.
- Q. Does the Beryllium-Copper ring installed in the aluminum rib at station 48 cause a corrosion problem due to the two dissimilar metals?
- A. There is a potential galvanic corrosion problem if the two materials make intimate contact in a moist environment. However, the Beryllium-Copper ring is adhesively bonded to the aluminum rib. The adhesive provides an insulated barrier that separates the two parts, thus preventing galvanic corrosion.
- Q. Is it possible that moisture, condensed inside the blade, will freeze during cold weather and cause blade imbalance?
- A. It is likely that small quantities of water will freeze inside the blade. Drain holes, located at several places on each blade, prevent significant accumulations of water. During operation at Clayton, N.N., we have not recorded any blade imbalance attributable to ice inside the blade.

TABLE I. - MOD-0A BLADE SPECIFICATIONS

DIMENSIONS

LENGTH	59.9 FT
TIP CHORD	1.5 FT
ROOT CHORD	4.5 FT
CHORD TAPER	LINEAR
TWIST	34°

MATERIALS

ALUMINUM	2024
STEEL	4340

AERODYNAMIC

AIRFOIL	NACA	23000
SOLIDITY		3%

STRUCTURAL DYNAMICS

FIRST FLAP	1.5 Hz
FIRST CHORD	2.9 Hz

INSTRUMENTATION

STRAIN GAGES:

LOCATION

ROOT END (STATION 40)
MIDSPAN (STATION 370)

MEASUREMENT

FLAP & CHORD BENDING
TORSION

ICE DETECTOR

SHUTDOWN WTG IF ICE IS GREATER THAN
0.020" THICK

MECHANICAL INTERFACE

CIRCULAR BOLTING FLANGE
24 - 5/8" DIA. HIGH STRENGTH BOLTS

ELECTRICAL INTERFACE

MS CONNECTOR, 55 PIN

BLADE WEIGHT - 2350 LB

TABLE II. - MOD-0A BLADE LOADS
NASA "RED LINE" BENDING MOMENTS

	MAXIMUM BENDING MOMENT (FT-LBS)	CYCLIC BENDING MOMENT PEAK TO PEAK (FT-LBS)
FLAPWISE, STA. 40	200,000	130,000
CHORDWISE, STA. 40	85,000	130,000

TABLE III. - MOD-0A BLADE COSTS

SERIAL NUMBER	DELIVERY DATE & LOCATION	\$/BLADE	\$/LB.
1004 & 1005	11-77 CLAYTON, N. M.	252,000	107.
1006 & 1007	5-78 CULEBRA, P. R.		
1008 & 1009	3-79 BLOCK ISLAND, R. I.	22,000*	93.*

* \$28,000/BLADE FOR STRUCTURAL MODIFICATIONS NOT INCLUDED.

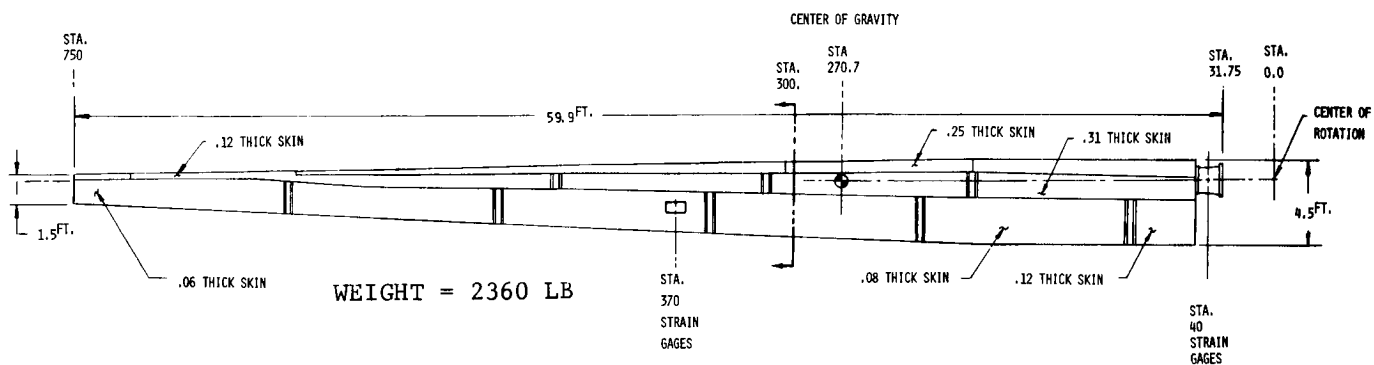


Figure 1. - MOD-0A blade configuration - planform.

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BLADE SECTION TAKEN AT STA. 300.

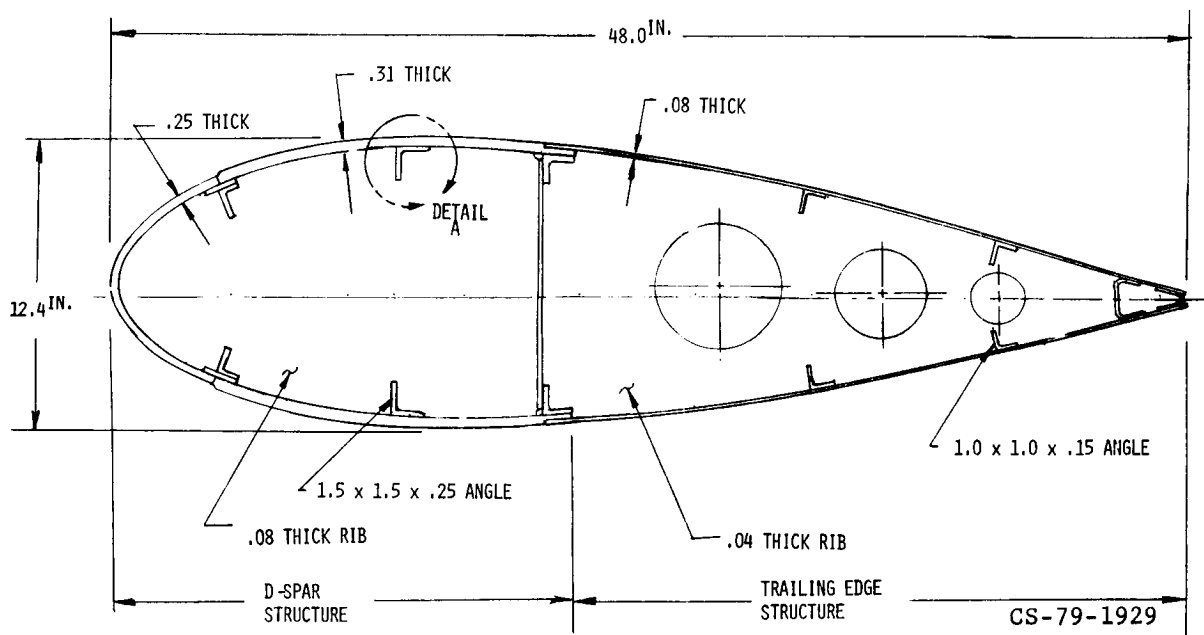


Figure 2. - MOD-0A blade typical cross section.

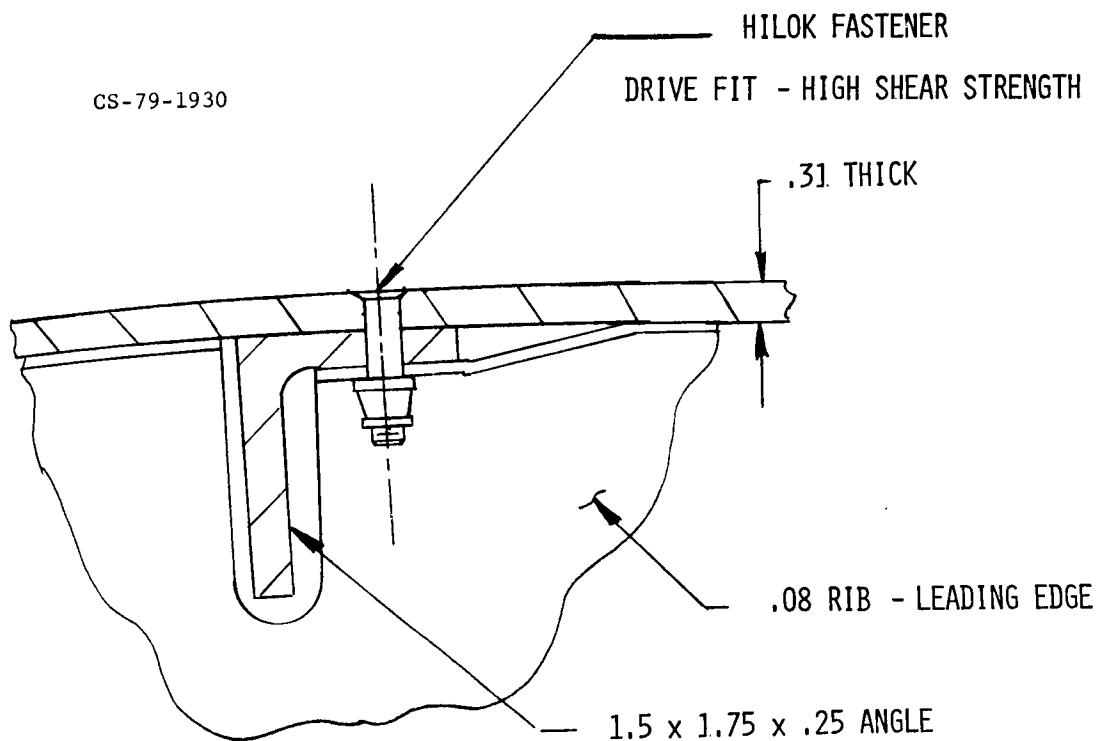


Figure 3. - MOD-OA blade fastener detail A.

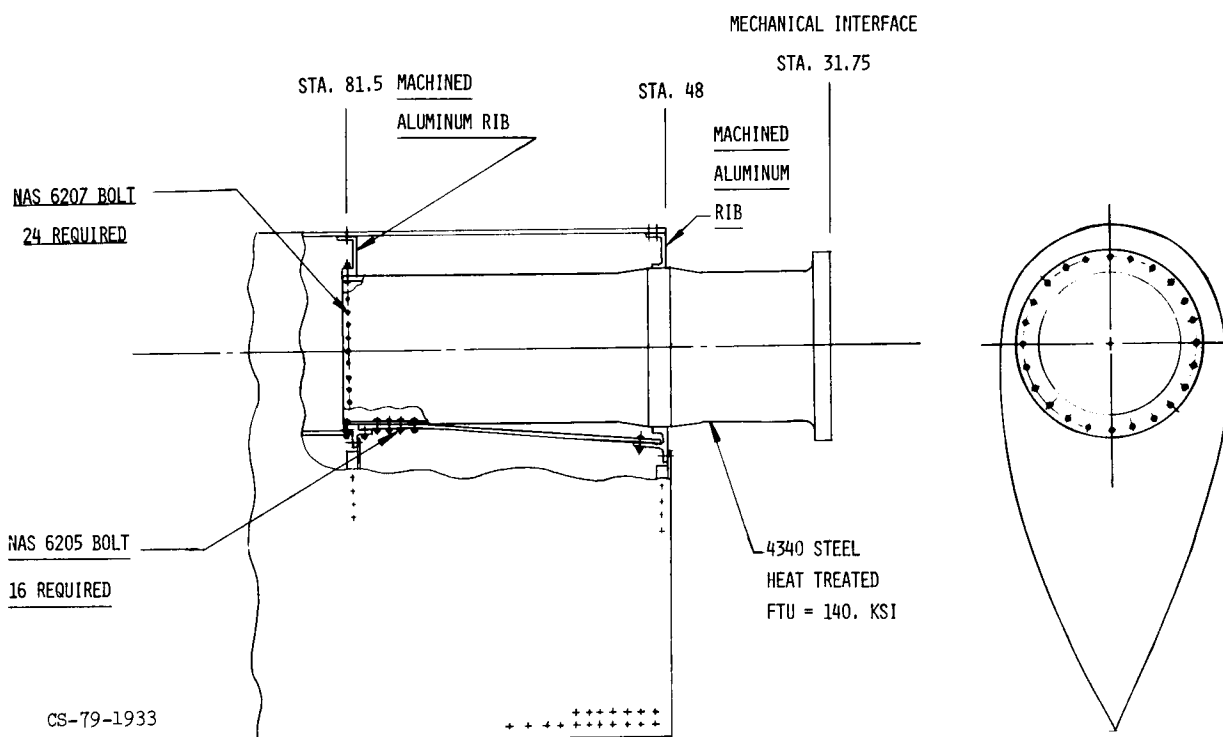


Figure 4. - MOD-OA blade root end details.

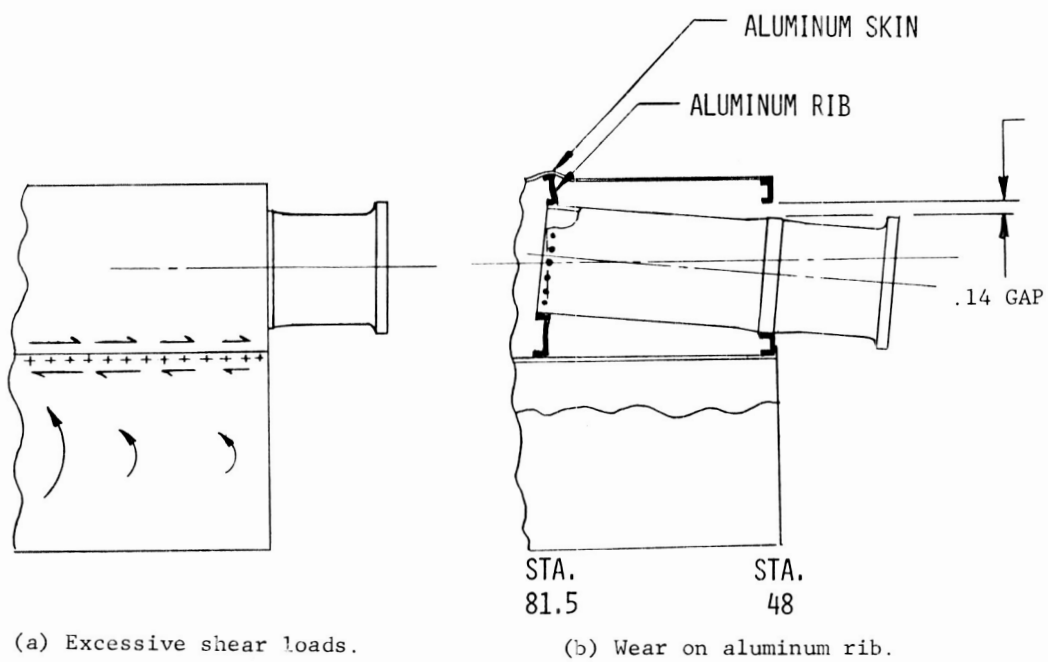


Figure 5. - MOD-OA detail design deficiencies.

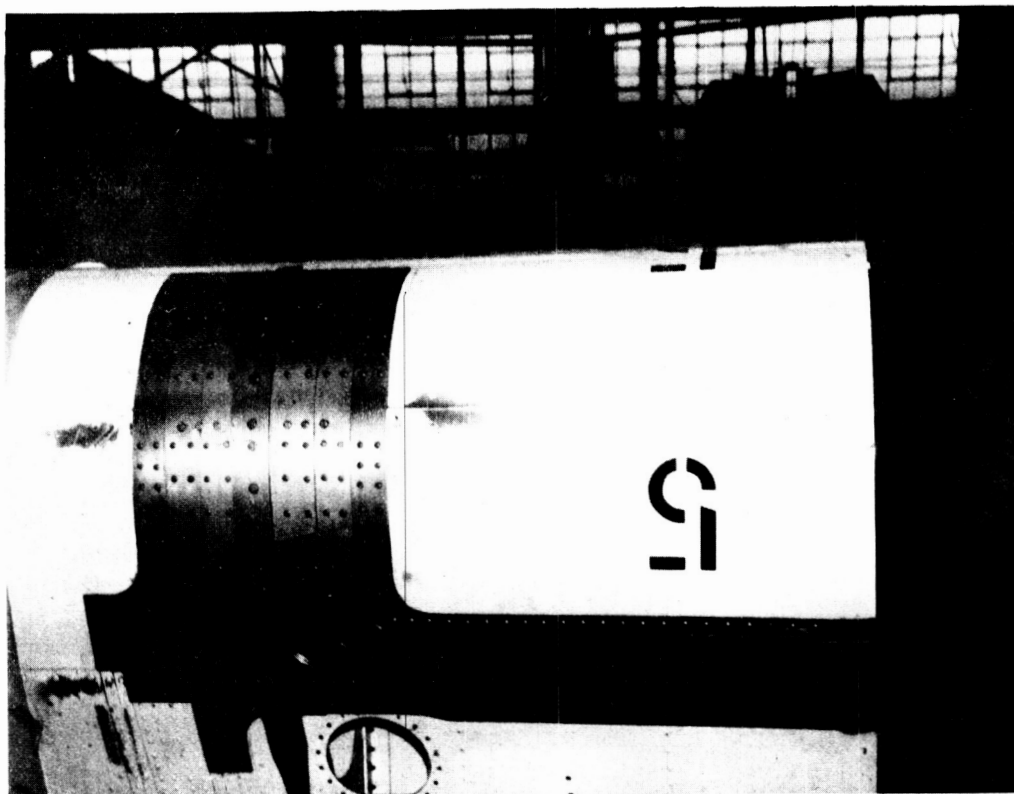


Figure 6. - Final installation of doublers on the low pressure side of blade SN-1005.

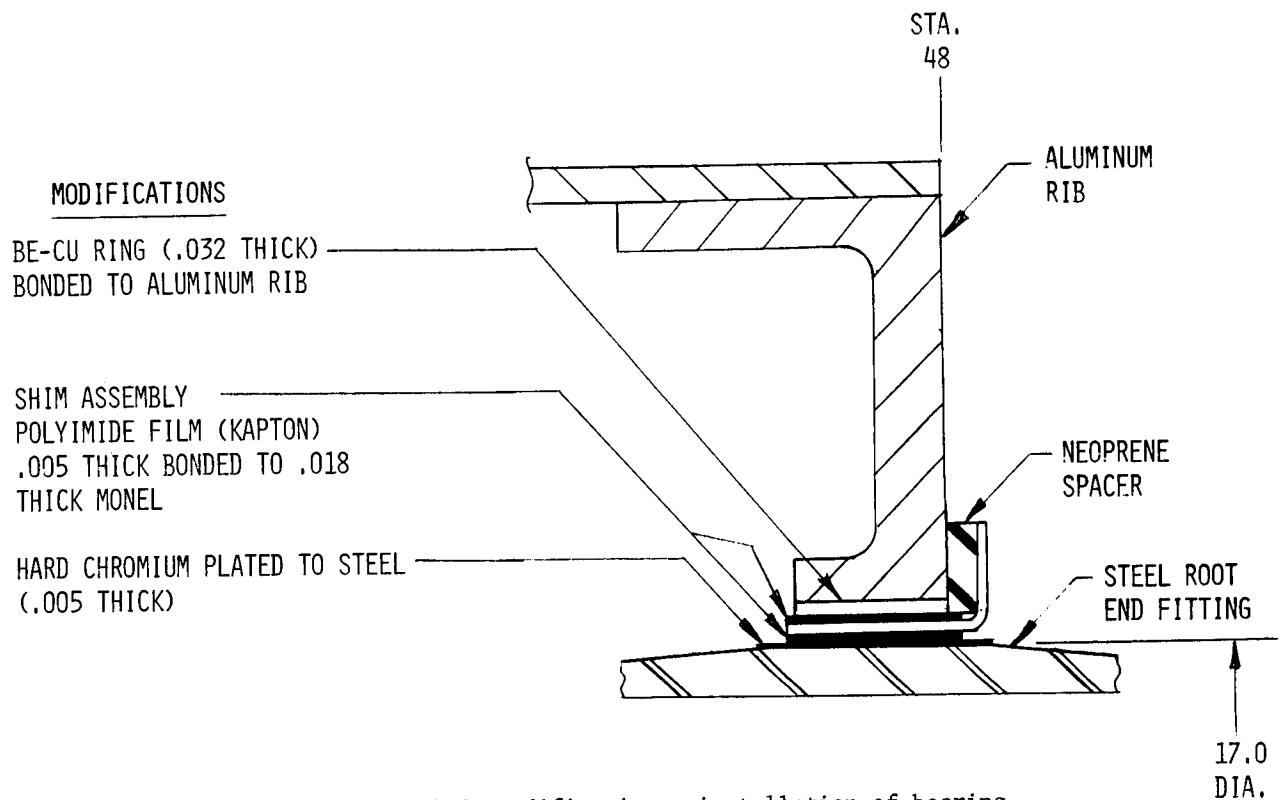
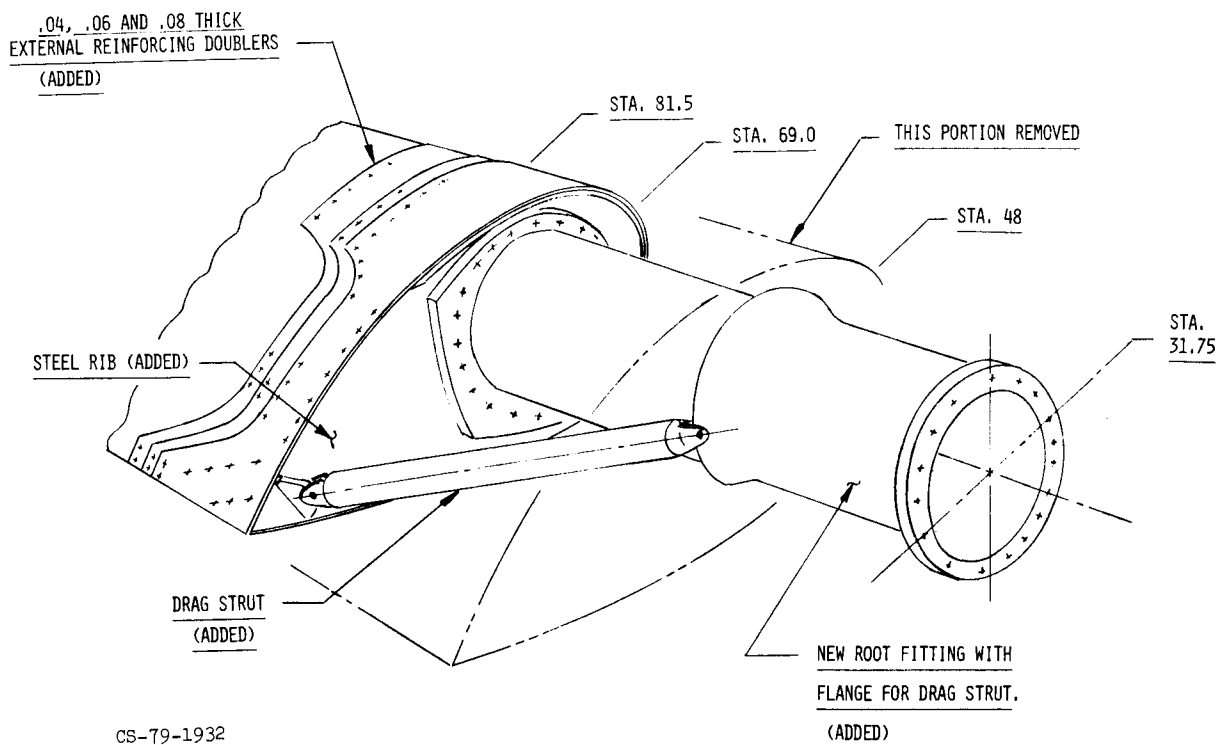


Figure 7. - MOD-0A blade modification - installation of bearing.



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Figure 8. - MOD-0A blade. Alternate modification.